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TO: NASA Headquarters
Washington, D. C., 20546
Attention: Code RET

SUBJECT: Theoretical and Experimental Investigation on Modulation Inducing Retrodirective Optical Systems, Contract NASw-721 (10-804) (10-1227), (Philco B003), Monthly Progress Report No. 12 for the period of 2 May 1964 to 21 May 1964

MEETINGS BETWEEN CONTRACTOR PERSONNEL AND TECHNICAL SUPERVISOR

None.

SUMMARY OF WORK ACCOMPLISHED DURING THE REPORT PERIOD

21/24

Considerable effort has been expended to ascertain the response of the cesium optical pumping system to audio-modulated microwave signals. Variations of signal have been observed for a number of parameters, including audio-modulating frequency, power levels, and resonance bulb response time for a well stablized microwave frequency; some data are included for response when the microwave frequency is swept through the resonance value at audio rates. In general, the results are similar to those previously reported for radio frequency resonances. Saturation effects are clearly indicated in these experiments, showing much slower falloff than the predicted ω^{-1} response when the depumping microwave power level is high.

Author

OTS PRICE

XEROX $ 1.60 ph

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EXPERIMENTAL ACTIVITIES

Experimental Apparatus

A fairly elaborate experimental technique was necessary to permit the microwave response characteristics of the cesium optical pumping cross modulation to be observed. The main problem is the narrow resonance linewidth which is ordinarily a few hundred cycles in well-shielded systems. For amplitude-modulated signals, two special pieces of equipment were purchased so that power at this narrow resonance frequency would be continuously, rather than sporadically, available for reliable response measurement. A Dymec 2650A Oscillator Synchronizer was obtained for frequency control with stability specifications $1/10^8$ short term (1 sec average) and $1/10^6$/week long term. Such an instrument will not allow the desired amplitude modulation to be performed at the klystron, and it was therefore necessary to arrange for some kind of chopping system which could serve as an amplitude modulator. Such an instrument was the E and M Laboratories X102VA ferrite variable attenuator which contains a coil whose current at the modulating frequency determines the level of attenuation. Up to 100-percent power modulation was found possible with this modulator for most of the low audio range, but high current requirements limited its use for this set of data to 1500 cps.

The experimental arrangement is shown in simplified form in Figure 1. The optical pumping apparatus is the same as previously used with minor changes. Most of the work has been done with a xenon-filled pumping lamp, rather than the argon ones previously used. Variations in pumping intensity were accomplished by placing a second linear polarizer in front of the circularly polarizing combination, effectively producing crossed polarizers; the $\cos^2$ law of Malus was used to calculate intensity passing the complex. The photomultiplier was our usual 7102, and although several dynode voltage levels were used throughout the work, all the data shown on any one curve represent relative values at one photomultiplier gain setting. The ac signal of modulation was filtered by a Princeton Applied Research Lock-In Amplifier JB-4, and great care was taken to translate all signal data to equivalent volts input to the amplifier for the various sensitivity ranges. The magnetic field current was provided by a silicon diode bridge rectifier with heavy filtering, and the input 110-volt ac voltage to the rectifier was controlled by a Sorenson electronic regulator. The magnetic field intensities used were about ten times higher than that

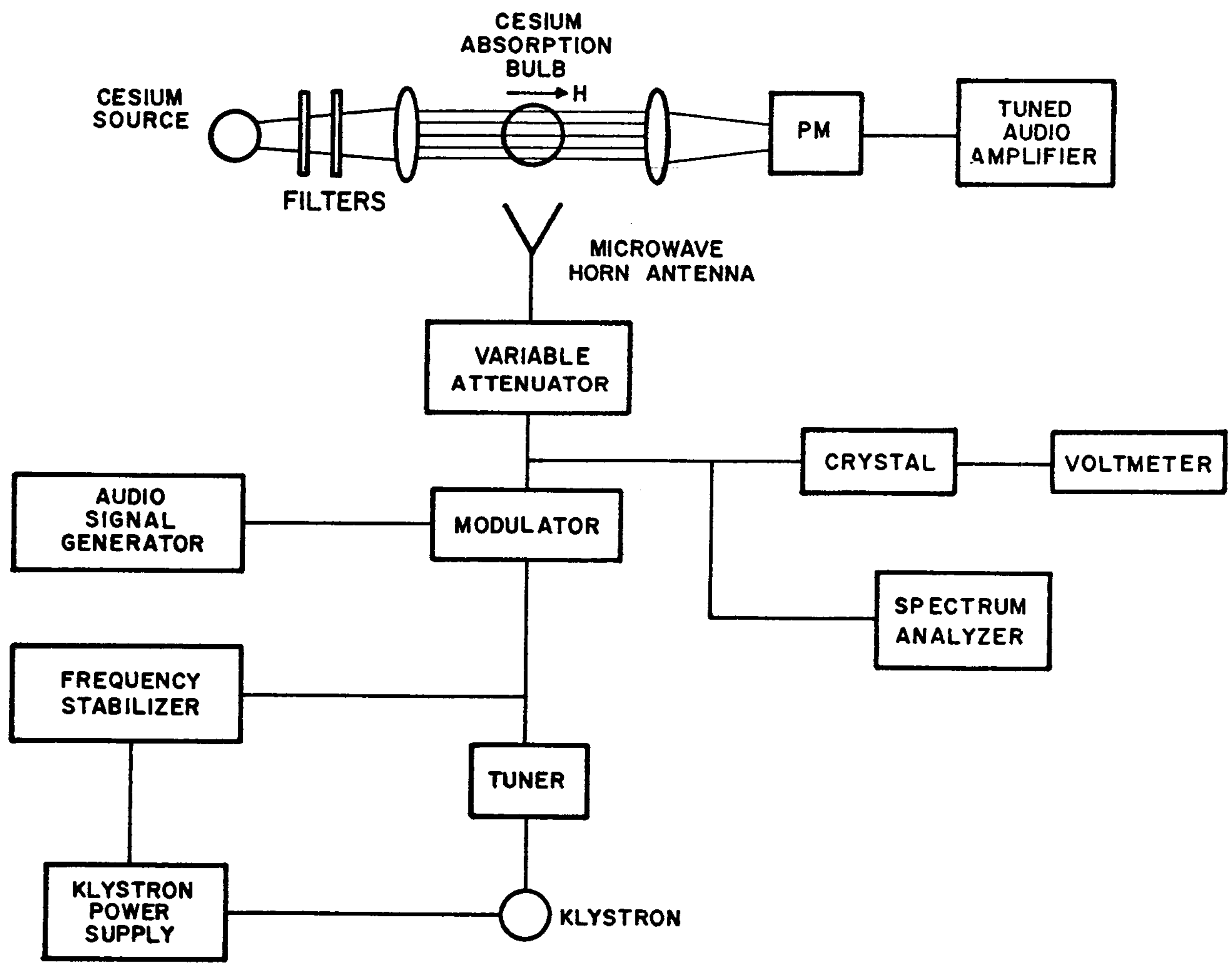

Figure 1. Cesium Microwave Resonance Apparatus

used previously because of the klystron frequency control feature. The Dymec instrument is crystal controlled, and in the desired range of frequency for the crystal available to us, we were able to stabilize only to 9166.473 or 9226.473 Mc/sec, with corresponding magnetic fields of 10.677 and 13.813 gauss. These two combinations of frequency and field were fine for checking the difference between right and left circularly polarized light in pumping. When switching from one combination to the other, we found that it was necessary either to change field direction or to rotate the retardation plate at the polarizer.

The microwave circuit was also fairly elaborate in order to ensure constant conditions. The modulator current required for 100-percent attenuation of the signal is variable with modulation frequency. Only 100-percent and 50-percent modulations were attempted over the range, but it was necessary to devise some means of determining the actual percentage modulation and index for holding the value constant. For this purpose, a Polarad Electronics Spectrum Analyzer SA-84 served very well for a visual oscilloscope display, but the required coil current was determined from the ac voltage developed in a crystal in the microwave line. This voltage was amplified 40 db by a Hewlett-Packard 450A amplifier and read with a Ballantine electronic voltmeter. The crystal voltage level was constant with frequency for a given modulation. The coil current in the modulator was supplied by a Hewlett-Packard 205AC Audio Signal Generator. Power output from the klystron was peaked with a slide-screw tuner and could be attenuated immediately before the horn antenna with a calibrated Hewlett-Packard X375A variable attenuator. Suitable attenuators, directional couplers, and isolators were used elsewhere in the microwave circuit to limit power where required. No attempt was made to determine the actual power level in milliwatts for this set of experiments in order to establish the minimum power level required for modulation and saturation onset. Only relative power as determined by the attenuator was recorded. The Sorenson electronic regulator which controlled magnetic field voltage was also used to control klystron power supply voltage.

The great care taken to provide the above assembly showed up two other experimental difficulties. The pumping source was known to be susceptible to air currents in pumping output intensity of the 8943-Å line, but it was found to our surprise that variations of a factor of 5 to 10 could be obtained when the room door was opened. To overcome this annoyance a glass cubical enclosure was constructed to cover the oscillator coil which energized the small spherical pumping light bulb. The other difficulty is a fairly large 60-cycle signal which appears at resonance even without current in the modulating coil. It serves as a good reference for tuning to the proper magnetic field value, but unfortunately it cannot be eliminated. The signal appears to be due to voltage variations at the klystron which the spectrum analyzer indicates as an effective modulation of about 40 to 50 percent. The crystal, however, does not recognize this as an amplitude modulation, and the variation must therefore be in frequency.

At the magnetic field strengths used, the various cesium resonance lines are well resolved. This may be seen in Figure 2 which indicates the level splitting resulting from application of the magnetic field. The frequency at which a resonance will be seen with microwaves is

$$f_R = 9192.632 \pm n\,(0.35\,H) \text{ in Mc/sec,}$$

where H is given in gauss and n represents the sum of the m_F values of the two levels and is equal to 7 for the (+4) to (+3) transition. For a given frequency of microwaves, tuning to the various resonances requires $7(0.35\,H_1) = 5(0.35\,H_2) = 3(0.35\,H_3)$, or the field currents are in the ratio 7:5:3, the strongest transition appearing at the lowest value of field current. Practically all data in this set of experiments were observed for the strongest transitions for both σ+ and σ- pumping, but one response set was observed for the (-3) to (-2) transition for σ- with our largest volume absorption bulb.

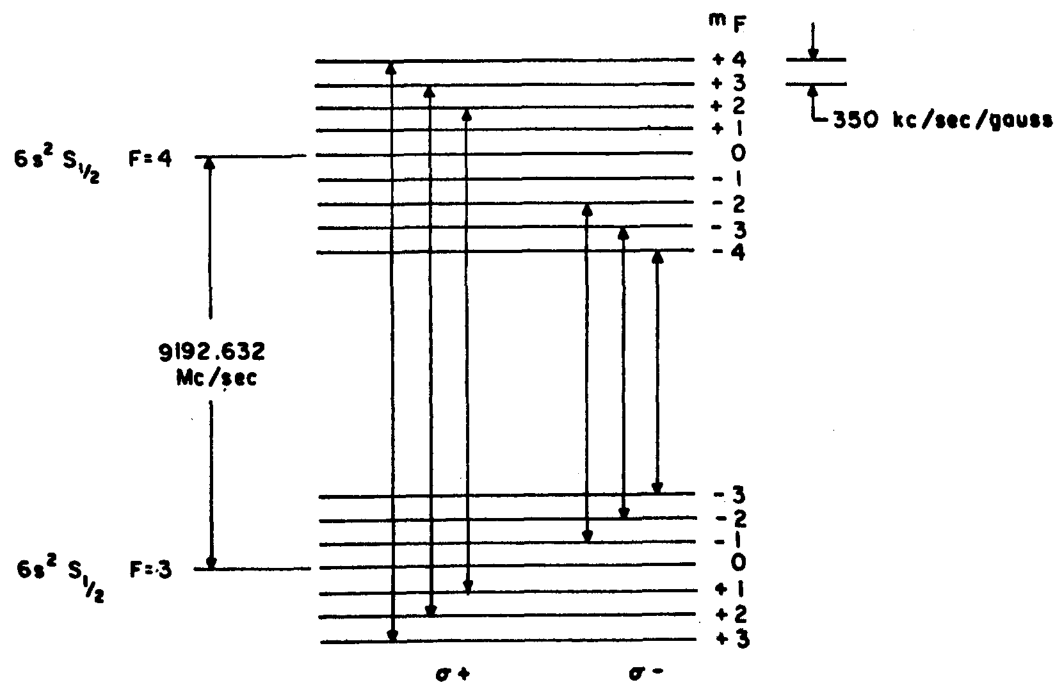

Figure 2. Level Structure of Field-Split Cesium Ground State Doublet

The above equation is useful to determine the bandwidth of the transitions in terms of frequency for observed magnetic field bandwidths. For the most uniform field used, the half-signal values at 50 cps show a field tuning range of about $\Delta H/H = 1/150$, providing a Δf_R of about 170 kc/sec. This bandwidth is very large compared with the cesium linewidth, but more precise work required to reduce the bandwidth was considered unnecessary. On the other hand, an attempt was made to increase the bandwidth by inserting two rectangular pieces of steel in the field at the top of the large absorption bulb used, and the resulting $\Delta H/H$ increased to about 1/10, with corresponding Δf_R approximately 2.5 Mc/sec. In the first case, without deliberate field distortion, the unstabilized klystron could not hold on resonance, whereas the field distorted case allowed a reasonably steady depumping signal to be observed when stabilization control was removed from the klystron circuit. It is certainly clear that a well designed nonuniform field can provide tunability over a wide range of magnetic field or frequencies, if so desired. The above remarks are pertinent for the (-3) to (-2) transition as well as the strongest one, both resonances appearing to show similar bandwidths.

The microwave power modulator has the interesting feature that, on every peak of the coil current, attenuation will occur. Consequently, the modulation frequency is actually double the coil frequency. The oscilloscope trace of the ac photomultiplier signal was not a good sinusoid, indicating that the harmonic content should be appreciable. Indeed, for one set of conditions, for both the 70-and 250-cps fundamental signal at the photomultiplier, the second harmonic signals were about one-quarter the fundamentals, and the third harmonic signals were about one-quarter the second harmonic. Just how much of this harmonic content is due to the method of modulation and how much is due to the cesium detection is difficult to ascertain.

Results

Figures 3 and 4 show the response of our large volume absorption bulb to power modulations of 50 percent and 100 percent at the audio frequencies of 50, 100, 200, 500 and 800 cps for various values of attenuation of power at the horn antenna. This large bulb contains cesium at room temperature with about 30-mm Hg pressure of neon as a buffer gas, with corresponding pumping time of about 50 milliseconds. At all frequencies, these curves show that the signal level falls off linearly with power beyond a certain range of values at which saturation effects occur. This saturation

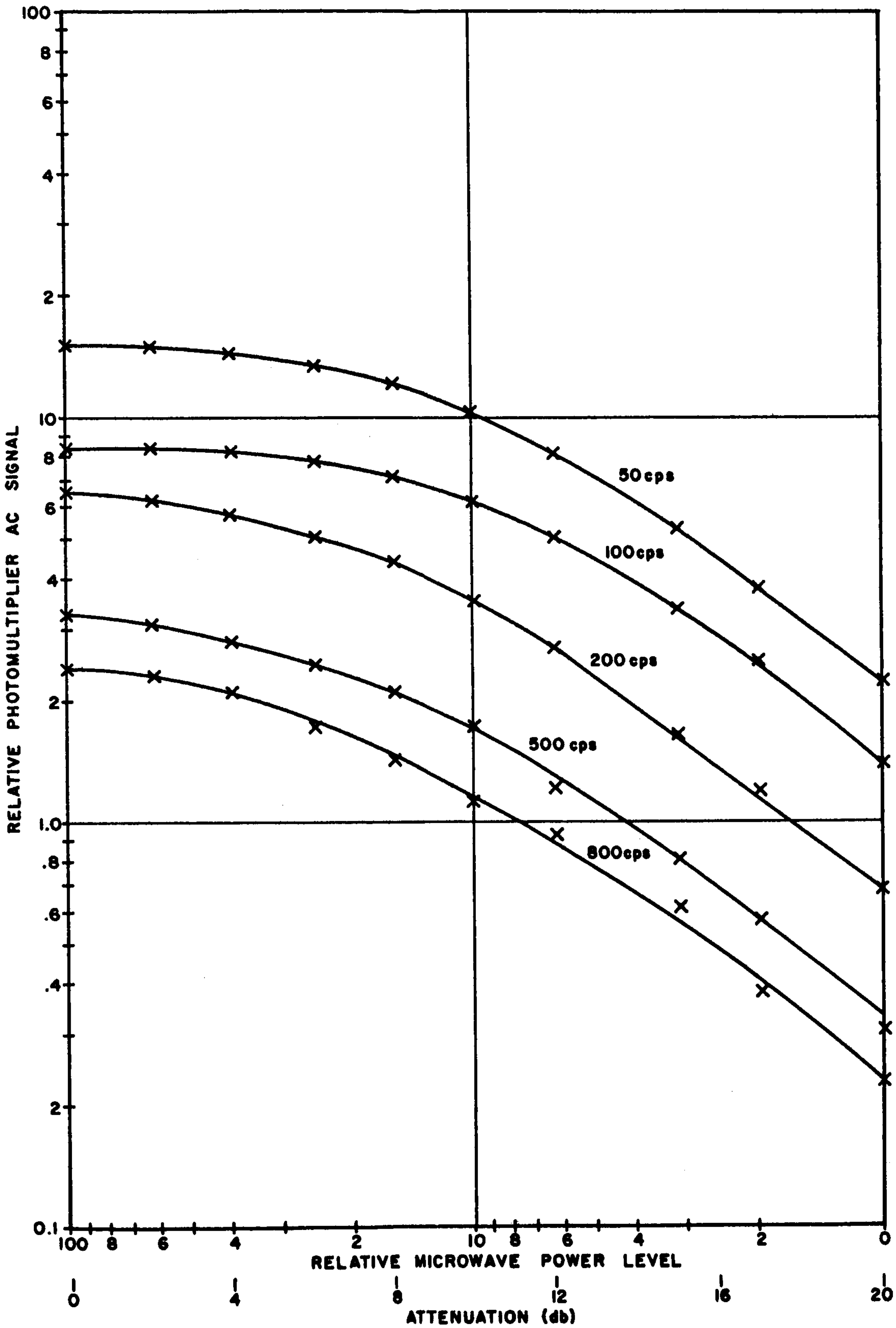

Figure 3. Cesium Microwave Resonance, Frequency Response to Amplitude Modulation at Audio Rates - 100-Percent Modulation Level (1000-ml Cell)

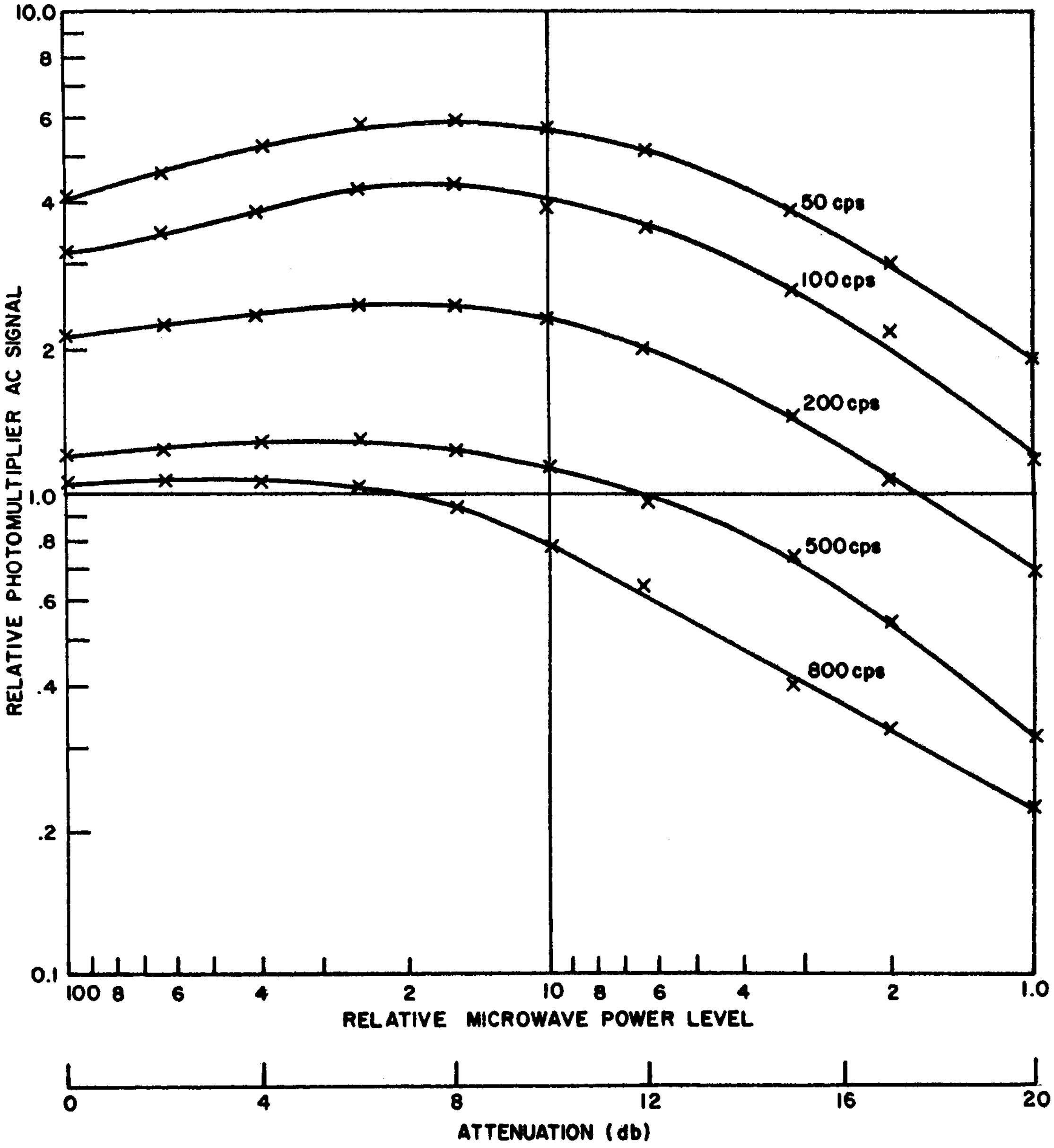

Figure 4. Cesium Microwave Resonance, Frequency Response to Amplitude Modulation at Audio Rates - 50-Percent Level (1000-ml Cell)

is especially marked in the 50-percent modulation cases, where half the power is used in depumping without being observable as an ac signal. The ratio of signals at 50 cps and 800 cps appears to be fairly constant over the power levels investigated, except for the 50-percent modulation case at high power.

This saturation at high power for the 50-percent modulation is especially apparent in Figures 5 and 6 which show a wider frequency response investigation for two absorption bulbs. Several bulbs were used, including

a. a 50-ml bulb, coated with Eicosane with no buffer gas;

b. an uncoated 50-ml bulb containing 30-mm neon;

c. a coated 50-ml bulb containing 30-mm neon;

d. the large bulb mentioned above.

Data are not available for the pumping and spin relaxation times of the small volume bulbs, but similarity of data in this experiment makes it appear that the variation in these time-constants is not as large as hoped for. Figures 5 and 6 are representative of all bulbs, with the exception that the fall-off in bulb (a) appears to be somewhat faster than the others. In general, one would conclude from the data that: (1) saturation effects provide a slower decline in response than low-power cases; (2) the decline at high power for the large-volume bulb is faster than for the small-volume bulb; (3) except for low-power levels, the predicted ω^{-1} fall-off is not realized, approaching more nearly $\omega^{-0.5}$ for the saturated case in the small-volume bulb.

Figure 7 shows the response of the large-volume bulb to modulation by sweeping microwave frequency through the resonance value at audio rates. This was accomplished, as described in previous reports, by applying a sawtooth voltage variation to the repeller electrode of the klystron. The resulting audio signal at the photomultiplier was monitored by the tuned amplifier; the amplitudes of the fundamental frequencies are compared in Figure 7 for varying power input. The fall-off in signal, linearly with power, is more well defined than in Figures 3 and 4 for the amplitude modulation cases. Resonance depumping occurs only momentarily in this sweep method, and saturation effects are not seen except at the very highest power levels available in this experiment. The ratio of signal levels at 50 and 800 cps

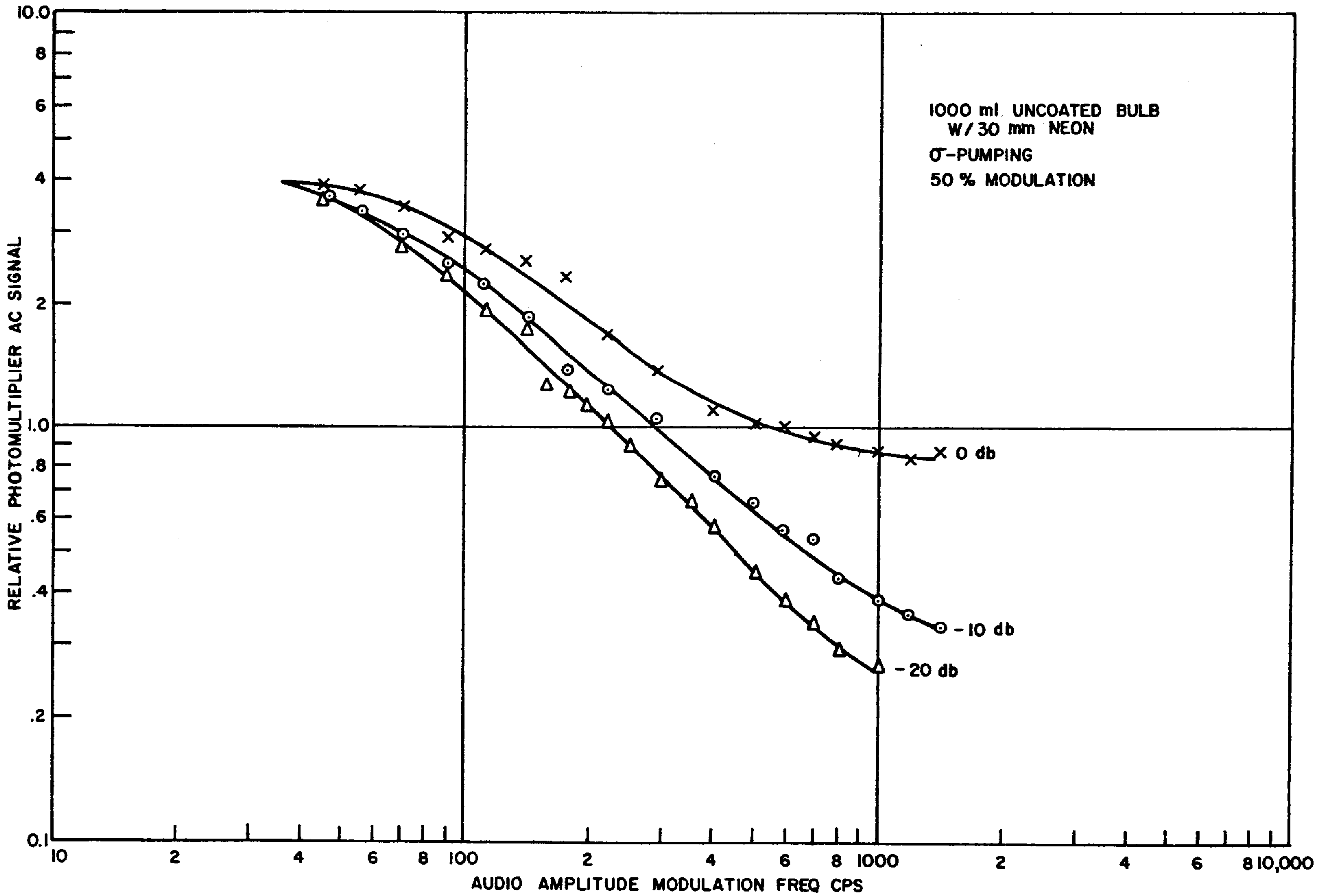

Figure 5. Cesium Microwave Resonance, Frequency Response to Amplitude Modulation

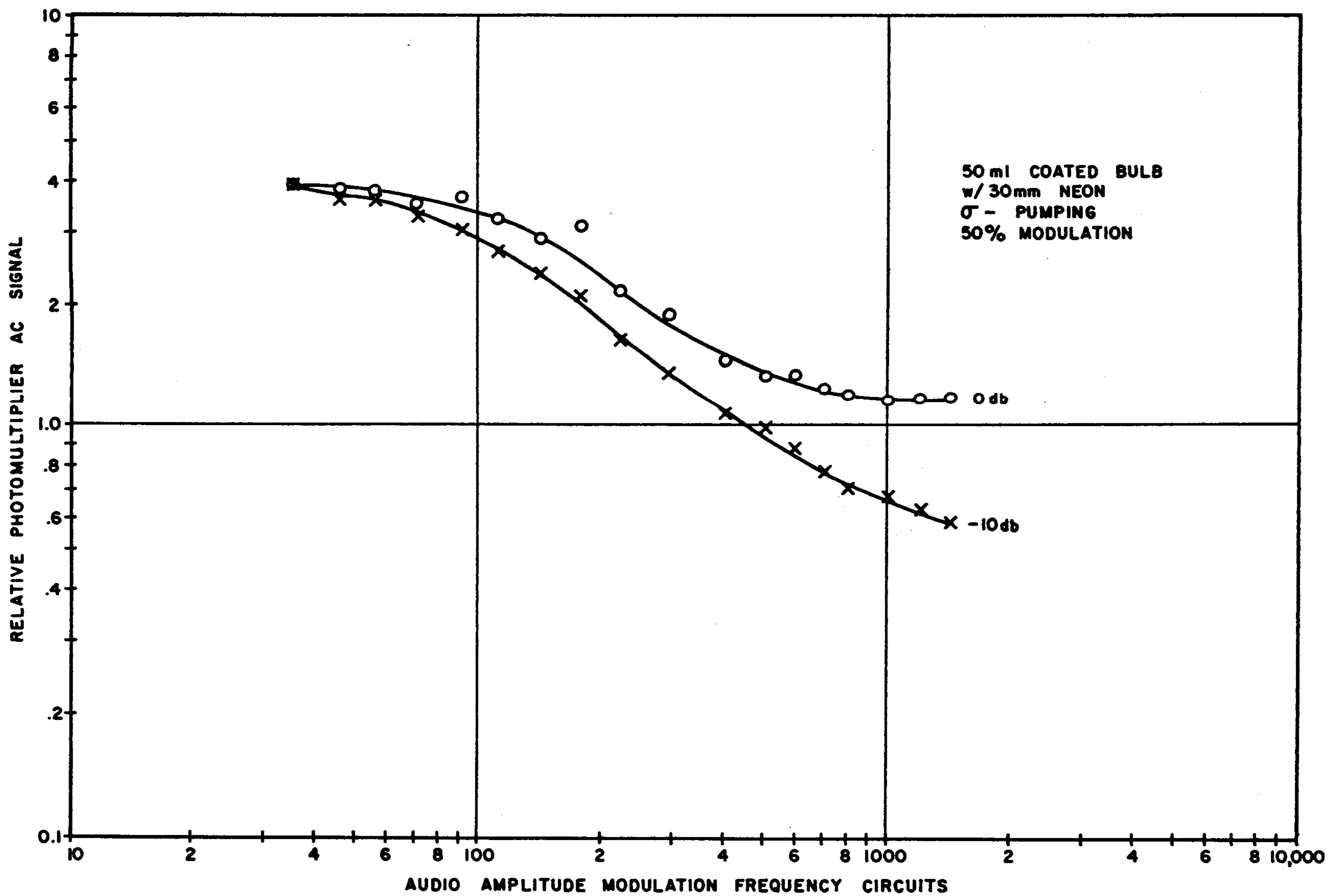

Figure 6. Cesium Microwave Resonance, Frequency Response to Amplitude Modulation

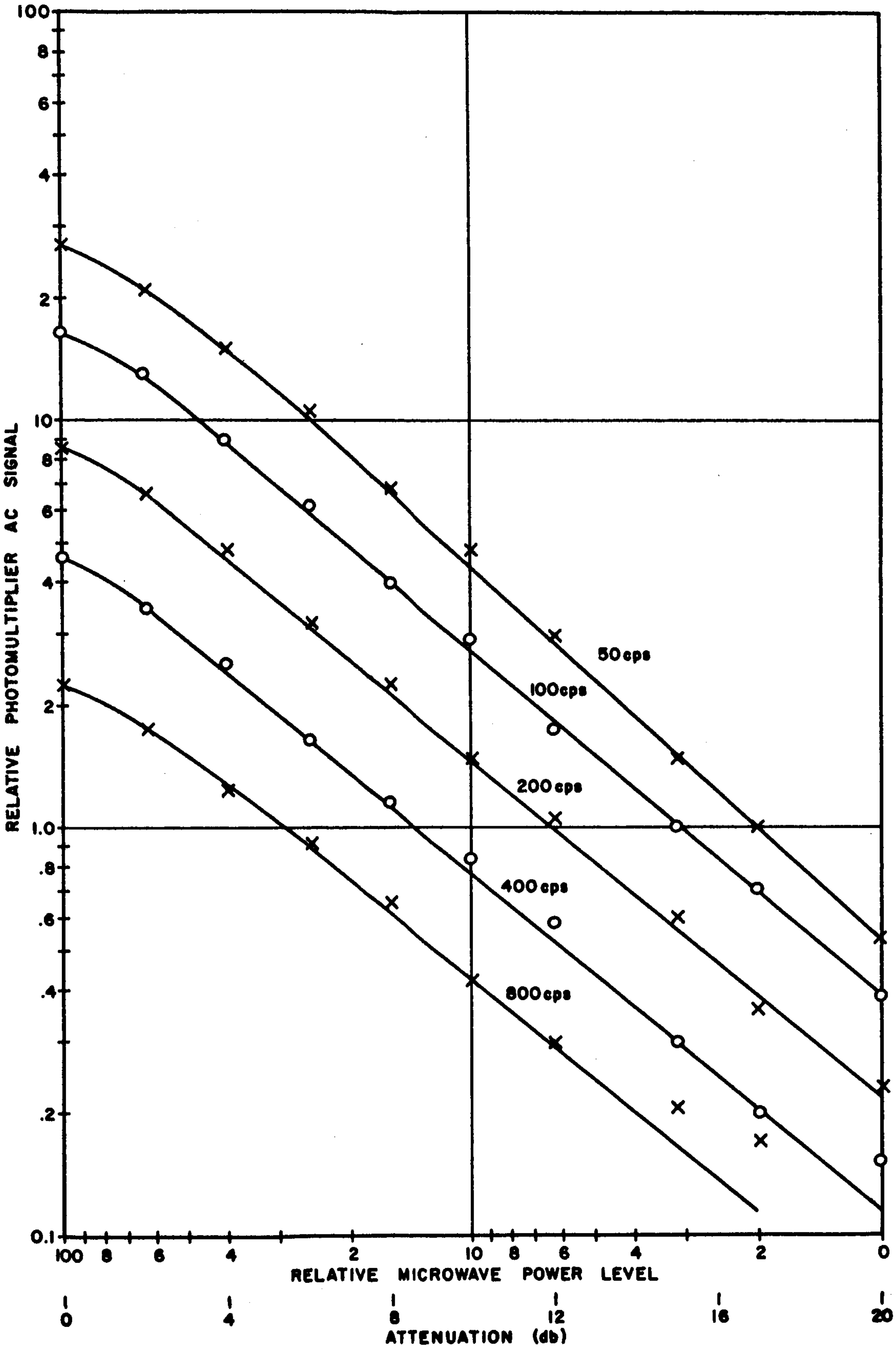

Figure 7. Cesium Microwave Resonance, Response to Frequency Sweep at Audio Rates (1000-ml Cell)

in the sweep method is similar to the ratio of signal levels at these frequencies for the amplitude modulation case. The two methods are actually similar in the sense that both types of modulation represent a chopped incident power at the cesium, the one chopping method attained by periodic removal of microwave power from the beam and the other attained by periodically swinging the microwave frequency off resonance. Harmonic content of the 50-cps signal for two power levels was investigated in this frequency sweep method, and the fall-off in harmonic signal amplitudes at 100, 150, 200 and 400 cps roughly varies inversely as the number of harmonic; the ratios are 1:0.55:0.35:0.26:0.11. This ratio of amplitudes in a Fourier analysis represents a sawtooth wave which is the type generally seen in an oscilloscope trace of the photosignal for frequency sweep resonances.

The effects of distortion of the field from the so-called uniform case are shown in Figure 8 for a 50-cps, 100-percent modulation microwave beam. The maximum signal due to modulation of the microwaves was found by fine tuning of the magnetic field current value, (H_R), in all cases at the maximum power level, and then the value of current was found at which the signal value fell to one-half maximum, $H_{1/2}$. Bandwidths are quoted for the range of coil current over which the signal registered between these limits. One attempt to distort the field was made by placing four symmetrically located lengths of nickel wire at the absorption bulb parallel to the lines of force. This actually did not widen the range of current tuning but did shift the value of current at which a signal maximum occurred and resulted in about a 10-percent reduction in signal. The distortion of field for which the data were taken was accomplished, as previously mentioned, by placing the rectangular steel pieces at the top of the bulb. Signal values were recorded for both values of field current which showed the half maximum signal, and the recorded values versus power level are an average of these readings because of similarity in fall-off.

It has been pointed out by R. B. Emmons of this laboratory that the cesium resonance detector appears to show a constant gain-bandwidth product because of the nature of the resonance and limitation of the signal for any absorption bulb to a definite value determined by a definite number of pumped atoms.

If this is the case, Figure 8 should show about an order of magnitude decrease in signal value when the bandwidth is increased by this amount. In the range of power below the saturation values, the ratio of signals for the distorted and undistorted cases does appear to be of the correct value

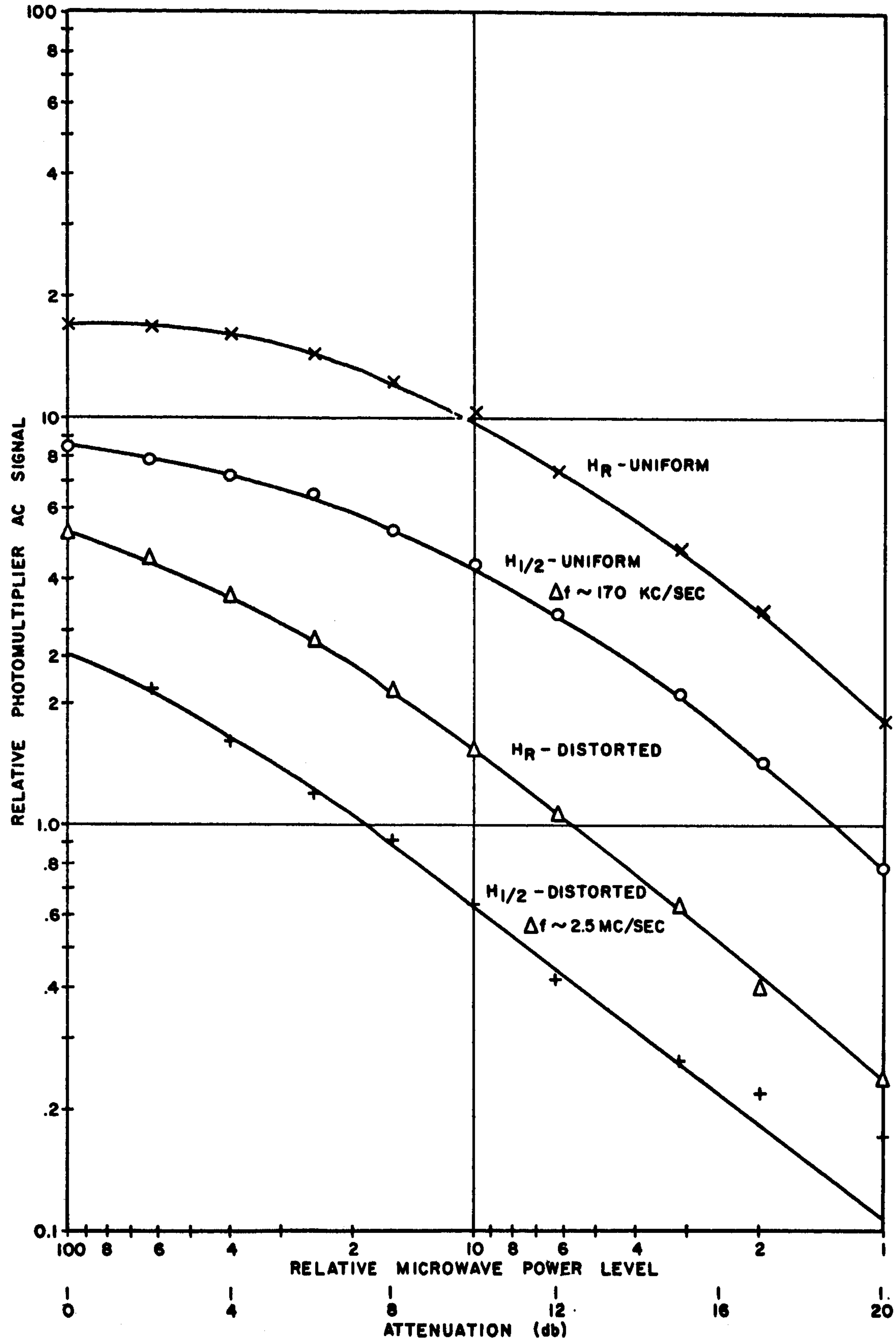

Figure 8. Cesium Microwave Resonance, Effect of Field Distortion on Signal Level; Variations with Input Power at 50-cps, 100-Percent Modulation

to support the gain-bandwidth conclusion. However, much more careful work would be required to show an exact correlation. The actual effect of field distortion is to reduce the number of pumped atoms which "see" the correct value of magnetic field strength and can react to the depumping signal. It is clear that, if one wishes to spread the depumping effect over a wider range of frequencies than the uniform field case presents, the received signal level must diminish; it can be strengthened for a given depumping power level only by increasing the number of pumped atoms. Data in the other figures indicate that the frequency response over the audio-modulation range generally follows a fall-off which approaches ω^{-1}, and this fall-off appears to be fairly independent of how the signal is obtained in terms of pumping or microwave power, as mentioned below.

The data mentioned above made it appear advisable to check the response characteristics at various microwave powers for several values of pumping intensity. We could not increase the pumping level of our light source, but we could attenuate the radiation, as previously mentioned, by means of rotating a linear polarizer between the pump source and circular polarizer. Data were taken at 50, 200 and 800 cps for microwave levels of 0-, 5-, 10-, 15- and 20-db attenuation. Both uniform and distorted field conditions were investigated; since the results are similar, only the uniform field case is presented. The data for 200 and 800 cps appear similar to the 50-cps case, except for signal level; Figures 9 and 10, therefore, concern only the 50-cps information. Note that in Figure 9 the signal level varies linearly with pumping intensity. Figure 10 shows the same datum points plotted against microwave power level, and linearity does not appear to exist between signal and depumping intensity. Leveling off of signal with saturation is shown nicely in this Figure 10, but an expansion of the scale between 0- and 30-percent microwave power level does show the linearity indicated in Figures 3 and 4. This set of curves in Figure 10 clearly shows that, for all but a few choices of operation, the microwave power level was too high and saturation resulted.

In the 1000-ml volume bulb used in this set of experiments, a comparatively low-modulation level was attained. Measurement of the dc change in photo current with applied magnetic field in pumping showed about a 30-percent change in transmission with optical pumping. One would ordinarily expect a large percentage of this change to appear in the cross-modulation signal. However, only about 10- to 15-percent signal level was observed. This low level of signal in depumping is probably

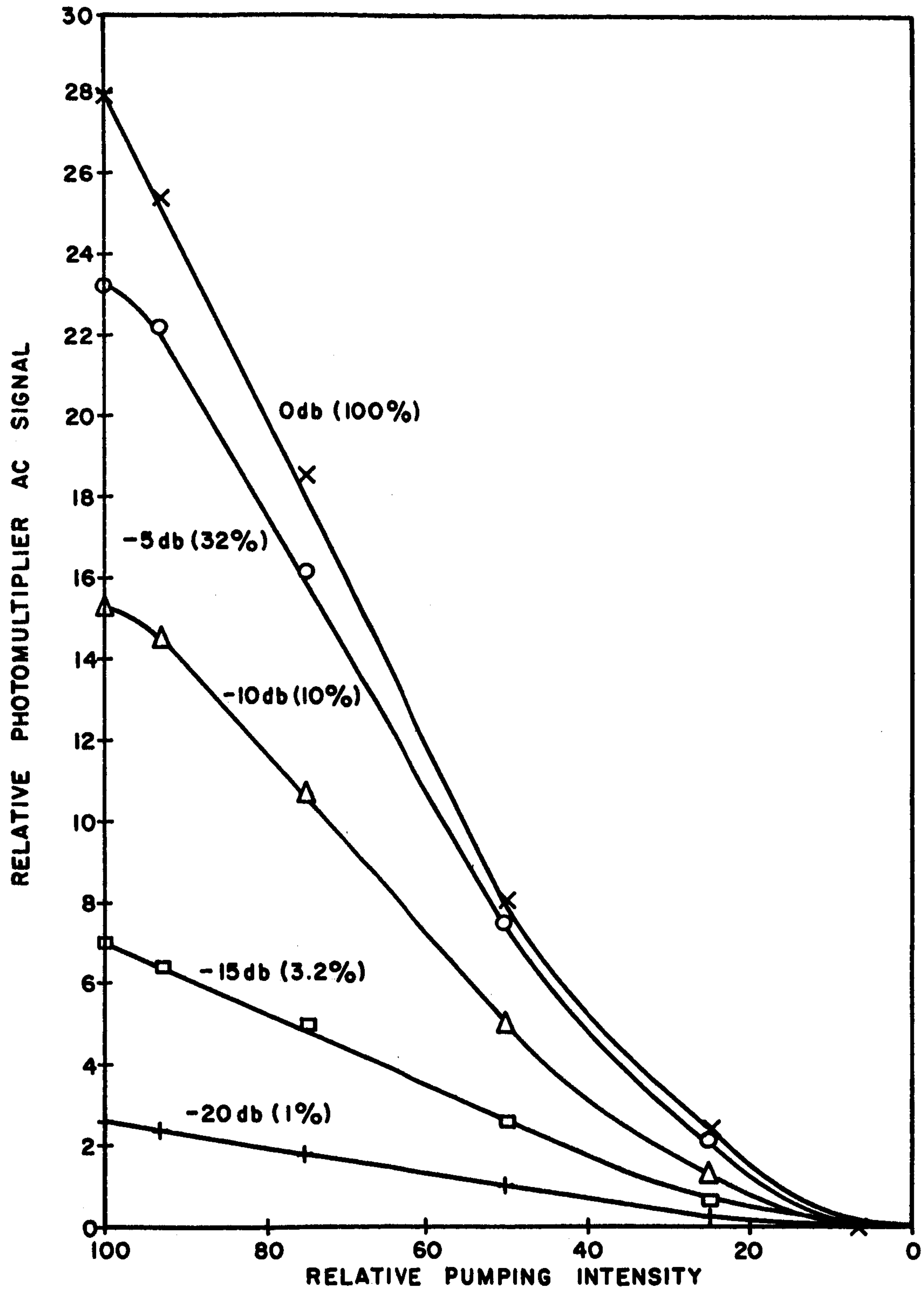

Figure 9. Cesium Microwave Resonance, Variation With Pumping Intensity at Constant Microwave Power - Uniform Field Case

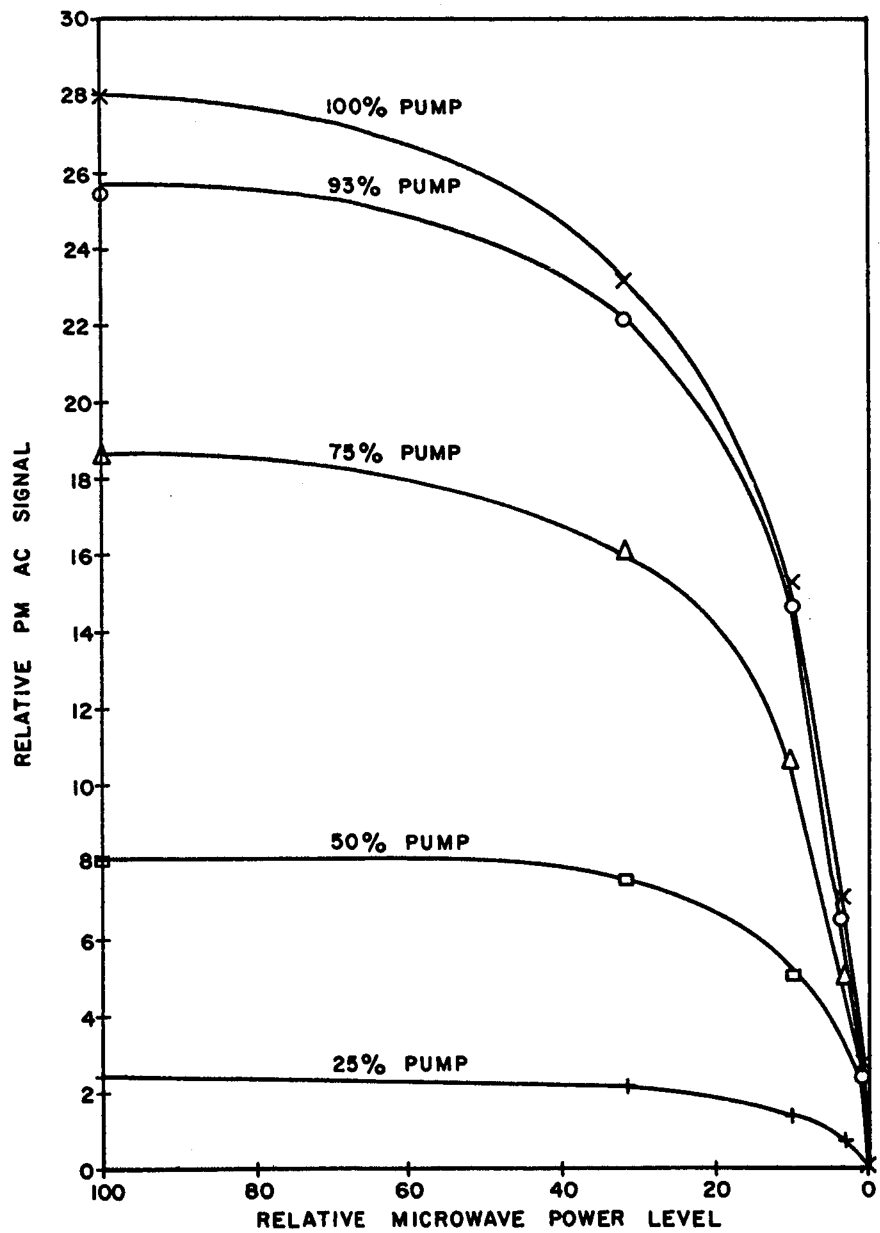

Figure 10. Cesium Microwave Resonance, Variation With Microwave Power at Constant Pumping Power - Uniform Field Case

due to the magnetic field nonuniformity (large bandwidth) which limits the number of pumped atoms which are tuned to the klystron frequency. The microwave horn radiation pattern may also be a source of inefficiency.

A plot was made of the 50-, 200-, and 800-cps data taken as a function of pumping power and microwave depumping power to show fall-off with frequency, as indicated in Figures 5 and 6. The ratio of the signal at 50 cps to that at 800 cps is very similar in the several cases, being about 7.5 for the highest microwave power and 9.5 for the lowest microwave power used. (Note that an ω^{-1} fall-off would make this value 16.) No radical change in signal level was noted for the decrease in pumping power over the range available.

The Carter equation concerning expected cross-modulation signals, which was developed in the Monthly Report No. 9, dated March 9, involves the three parameters of pump power, P; depump power, D; and a relaxation rate which is the inverse of an effective relaxation time. Inspection of this equation in terms of signal level and frequency fall-off indicates that some correlation of the reported data may be possible. If one assumes in this equation that the relaxation term may be represented by a frequency, ω_0, and selects values of P and D which are multiples of this value, the frequency fall-off appears to be reasonably constant over a wide range of P and D. Naturally, the signal level is low for small values of P and D compared with ω_0 and is high for high values of P and D. The best frequency response is indicated when both P and D are large compared with the ω_0 (small relaxation time); similarly, the best signal level occurs for this condition. If P is large and D is small, good frequency response occurs, but the signal level is low. If D is large and P is small, the response is about the same, but the signal level should be higher.

Our microwave data do not show large changes in frequency response for changes in P and D, but it is interesting to note that the same signal level was observed for -20-db microwave and 100-percent pump as for 0-db and 25-percent pump, somewhat in corroboration of the above analysis. Low microwave and pump powers showed the worst response, while the high combination of powers gave signals about 100 times the worst values. The equal signals quoted for the above two combinations were at a level between these two extremes.

COMPARISON WITH OTHER DATA

The frequency fall-off less than the predicted ω^{-1} led us to reinspect our other data, and particularly the chopped light optical cross modulation. It will be recalled that practically all responses with the optical modulation showed the ω^{-1} characteristic. The radio-frequency modulation method produced somewhat confusing data because of the narrowness of resonance in frequency, saturation effects and our method of using our tuned amplifier. However, this radio frequency information seemed to show also the ω^{-1} fall-off to the best of our ability to measure at the time.

In the process of analyzing the microwave data, it seemed wise to plot the signal-frequency curve both in terms of indicated scale reading of the tuned amplifier and in terms of equivalent volts input to obtain the same scale reading. A large discrepancy in slope of the curves resulted, and this was traced to severe nonlinearities at the low values of each sensitivity range of the amplifier. The more correct procedure, of course, is to translate to equivalent volts input, but this has not been done until the microwave data indicated the need. Apparently, the microwave apparatus stability was much better than previously attained, and changes in output were not recognized. Reevaluation of the optical modulation data shows, on the one hand, that the frequency fall-off of response is much slower than ω^{-1}, and, on the other, that several breaks occur in the fall-off curve which are traced to impedance changes in switching between sensitivity ranges on the tuned amplifier. Several of these optical cross-modulation sets of data have been replotted, and the same fall-off appears. The completeness of the microwave experiment suggests that the other two methods should be tried again to investigate more thoroughly the slow optical fall-off and the saturation effect with both optical and radio-frequency energy. The slower fall-off is certainly more favorable from the point of view of application to optical communication, and more quantitative information for comparison of the three techniques is suggested.

CONCLUSIONS

The period of this report concludes the contract year, and this constitutes the final monthly report. A review of activities and recommendations are expected to be included in the required summary report. Needless to say, our extensive activities with optical pumping of cesium vapor indicate our recommendation of this technique for passive MIROS communications.

Our initial aim was the investigation of a workable scheme in a passive device, and analysis has shown that several are possible, each with one or more limitations which make long-distance, wide-band communications difficult. There is no doubt that concentrated engineering development activities could produce improvements in these techniques which may very well lead to usable devices, as, for instance, in the band edge modulation and the F to F' color center conversion in crystals. Aside from the light source development which is needed in any case, the optical pumping technique appears to involve less development time because of its simplicity of construction and operation and correspondingly fewer areas requiring attention. Its applicability to cross modulation has been adequately shown with four techniques which involve radiation frequency ranges spanning the electromagnetic spectrum from audio (axial field variation) to radio frequency (Zeeman resonances) to microwave (hyperfine-Zeeman resonances) to optical effects. It is sincerely believed that one or more of these modulation processes may well be suited to the optical communication needs of the future.

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